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SCIENTIFIC AND TECHNICAL ISSUES RELATED TO MAYAK AND CHERNOBYL SITES

Summary of a Round Table Discussion

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INTRODUCTION

At the conclusion of the *Fourth USA/CIS Joint Conference on Hydrologic Issues of the 21st Century: Ecology, Environment and Human Health*, held in San Francisco, November 7–11, 1999, a round table discussion was held to discuss the Mayak and Chernobyl sites. The panelists were Dr. Evgeniy Drozhko, Mayak Production Association, Russia; Dr. Michael Foley, Pacific Northwest National Laboratory; Professor Jack Sharp, University of Texas at Austin; Professor Viacheslav M. Shestopalov, Radioecological Center, National Academy of Sciences of Ukraine; Professor Paul Witherspoon, Lawrence Berkeley National Laboratory; and the Session Chair was Thomas Nicholson, Senior Hydrogeologist, U.S. Nuclear Regulatory Commission.

Dr. Chin-Fu Tsang, Conference Technical Chair, introduced the panelists and Nicholson. Nicholson mentioned that the round table discussions follow from papers presented in the "Chernobyl Environmental Studies" and the "Mayak Environmental Studies" sessions of the Conference.[*] The organizers of this session believed that it is of interest to discuss the Mayak

[*] See C.R. Cole, K.A. Hoover, M.G. Foley, M.D. Williams, E. Drozhko, L. Samsonova, N. Vasil'kova, A. Zinin, G. Zinina and K. Ter-Saakian, "Development and Calibration of Three-Dimensional Regional Hydrogeologic Model for the Mayak Site, Urals" and R. Freed, L. Smith, and D. Bugai, "Migration of Strontium-90 Within the Borschi Watershed Near Chernobyl, Ukraine," in the Special Issue, Part 1.

and Chernobyl sites together. Much can be learned by considering the similarities and differences in scientific issues between these two sites.

At the start of the session, Nicholson asked a series of questions that had been provided earlier to the panelists and conference attendees. These questions served as an introductory overview and were referred to repeatedly during the session to facilitate dialogue between the panelists and session participants. These questions are given in the next section. General discussions on the scientific and technical issues related to the two sites then follow, along with summaries of specific research work discussed by two session participants. Finally, a few remarks taken from the final part of the panel session conclude this paper.

QUESTIONS TO FOCUS DISCUSSION

The following questions were prepared and presented to the meeting by Nicholson to help focus the ensuing discussion:

1. How have the studies presented at this conference advance the state of the science (and art) in contaminant plume characterization, control, and remediation?

2. What are the significant lessons learned from the Mayak and Chernobyl site studies, in particular, what are the insights from characterizing and monitoring contaminant plumes or from mitigation and remediation programs?

3. Using lessons learned from these site studies, what can we say about practical remediation options and related confirmatory monitoring strategies? For example, is monitored natural attenuation a credible remediation option, and if so, at what temporal and spatial scale is it effective?

4. For the Chernobyl site, what significant lessons learned would benefit the design, emplacement, and monitoring of nuclear reactor containment features? Is ground-water mitigation for potential severe reactor accidents a credible concept, and what important site features need to be considered?

5. How will ground-water contaminant plumes at the Mayak and Chernobyl sites evolve and interact with surface-water bodies such as wetlands downstream? What monitoring programs would be useful in confirming (or disproving) our intuitions?

6. What technological challenges need to be resolved to improve the effectiveness of remediation options, to build confidence in the related confirmatory monitoring programs and ground-water transport modeling, and to demonstrate improvement to the public health and safety of the affected communities?

7. How can timely information from international cooperative studies be shared with other scientists?

8. How can future technical analyses, particularly the modeling of selected datasets, be cooperatively pursued by the scientific community, and how can the derived information and lessons be shared with the international community?

9. What specific datasets are available for testing ground-water transport models?

10. What datasets are available for testing atmospheric depositional and dose assessment?

11. Identify significant citable sources of information for the lessons learned and major technological advances identified from the Mayak and Chernobyl site studies. Which citable sources describe the site-specific datasets, conceptual models, field characterization and monitoring programs (including instrumentation and techniques used), and modeling results?

SUMMARY OF GENERAL DISCUSSION

The following summary of the discussion was developed in part from an audio recording of the session, and through a partial transcript developed from the recording. The panelists and session participants addressed the majority of the questions posed by Nicholson, but not necessarily in the order presented. Comments are not generally attributed to specific speakers but are presented as group dialogue. Active participation involved not only the panel members, and the panel and technical committee chairs, but also session attendees, particularly Valery Mironenko, Alex Pek, Charles Cole, Hal Wollenberg, Boris Faybishenko, Philip Long, Marcel van der Perk and others. The points presented below do not follow the sequence of the discussion during the meeting, but have been rearranged so that the summary presented here follows to some degree a logical order.

One of the key points that emerges from the papers and discussion is that there is an understood need to make predictions on the movement of radionuclides in the natural environment which results in our need to use a model. A model is defined as a simplified description of a system or process that can be used as an aid in analysis or design. In order to practically simulate the system and its processes, we have to simplify the system. The challenge, however, is that our models, which are to be capable of simulating what will happen in the next 100 to 200 to 10,000 or more years, are not presently testable. What sort of systems do we set for verifying these models? This was pointed out to be especially true for modeling variable density fluids. Also, how much confidence do we have in the models? The data collected at the two sites, Mayak and Chernobyl, are impressive. If we are looking for a database to test these models, these databases look almost ideal. Furthermore, the databases which demonstrate relatively rapid rates of vertical migration at Chernobyl, and the relatively fast horizontal migration from Lake Karachai at Mayak would also prove useful in testing simple one- and two-dimensional transport models.

It was noted that there is an enormous amount of data for both the Mayak and Chernobyl sites. However, one fundamental problem is the organization of these databases. Reliable data is needed to model the Mayak and Chernobyl sites. The use of both sophisticated and simple models will rely heavily on these data, and the issue of model validation will rest on the reliability and organization of these databases. For example, significant resources have been expended in developing an atlas of areas in the Ukraine that were exposed to cesium-137 and strontium-90 emanating from the Chernobyl accident. Details on the nature and distribution of atmospheric deposition within the 30-kilometer exclusion zone are needed to serve as technical bases for modeling purposes. Presentations at this conference indicated that 60% or more of these contaminants were "hot particles" from the destroyed reactor core. An organized and reliable database will help address the question of what long-term effects the "hot particles" will have on the environment. Field data and analyses related to the "hot particle" deposition problem may also benefit studies of decommissioning reactors elsewhere.

The uncertainties present within a database are very important. Some uncertainties may be man-made; sufficient money for investigations to remove some of those uncertainties was not available. Other uncertainties may be beyond our control. For the predictive range of numerical models, we should try to predict solutions that will be required for remediation activities at a particular site. We should have ongoing, permanent models capable of incorporating new data that might affect the workings of a model. While long-range modeling is a valuable and useful exercise, Dr. Drozhko (the chief engineer from Mayak) stated that a model should be able to predict situations as much as 20 or 30 years ahead which would be enough for any practical purposes. The Mayak and Tomsk sites are probably representative in that respect, because there are datasets covering approximately the same period as the period to be predicted. Dr. Drozhko did not think that making a database generally available was a viable option. Rumors basically spread in accordance with the laws of diffusion: they diffuse and become unrecognizable. Then there is no control over how a particular dataset or part of a dataset might be used by some people. He believes that a definite collaborative project with research groups is the best foundation for multigroup use of datasets.

Many of these data, even the raw data that have been calibrated against laboratory standards, are still point samples taken out of a time series for a particular location. So even if we have the data in a three-dimensional matrix that identifies their elevation, latitude, longitude, and all the hydrogeochemical variables that may affect the composition, that still is just one point in a time series: How the composition, which may even be metastable, arrived at that place in space and at that place in hydrogeochemical composition space, is crucial to the interpretation of those particular data. If that entire temporal and spatial history is lost, the use of those data in some other study becomes meaningless, and it may actually lead to the wrong conclusion.

A general database is not efficient for good results. If a geological survey drills boreholes for one objective (for example, for waters supply), and then others would like to use these data to assess the risk of contamination, one would not obtain the optimal result. This was proven at Chernobyl. Monitoring of contamination should be based on the most important and fast migration pathways, which mainly determine the contamination process. The location of observation boreholes should then correspond to the landscape, recharge-discharge locations, and to our knowledge of migration patterns.

An example is the first primary model for the Chernobyl zone that was set up to include only general transmissivities and characteristics of the intermediate surface and ground-water system. This first model enabled very favorable forecasts. Next, the project tried to take into account not only the average values from horizontal transmissivities and permeabilities, but also vertical migration. The flow is also affected by the landscape and fault zones; and the processes involved are not only surface but also of deep origin. It is irresponsible for us to try to forecast for hundreds of years if we cannot fully characterize these processes. For this reason we need a permanent model that should include not only the modeling code but also a system of field observations and specially organized testing sites.

Data must be handled properly. We need to know the quality of all the data that we are going to use. On the other hand, it would be extremely useful to have more research groups model the system and compare the different conceptual-modeling approaches. One proposal is the approach that the international cooperative INTRAVAL project used a few years ago. It was a cooperative project in which the data and information were shared among several research groups, who used different models to study the data. There were regular workshop meetings held once every six months or so to review and discuss results, and all of these activities were under the oversight of an active secretariat and the research group who provided the data.

It was agreed that cooperative efforts are important, and we need to work in ways that would allow us to use the available resources. Charles Cole of Pacific Northwest National Laboratory commented that the code and studies that they have been pursuing in cooperation with their Russian colleagues have helped to advance the way they investigate remediation options at the Hanford Reservation in the United States. Their code, developed as part of the work on this Russian cooperative effort, is now being used directly at the Hanford site. In terms of these cooperative studies, we must look for win-win situations in which we can work on issues important to both countries, and solve problems of mutual concern.

Another important observation dealt with the effects of subtle landform topography on radionuclide migration in the relatively flat country at the Chernobyl site. It appears that slight changes in topography can concentrate radioactivity in soils. Extensive flooding in the region, and local streamflow events also have had a significant effect on radionuclide migration into surface-water bodies, accumulations in the shallow soils and alluvial deposits, and the underlying water-table aquifer. The role of river flow and accumulations in storage reservoirs that may be used for irrigation are important research topics, ones that could be assessed using the Chernobyl data. The relationships between atmospheric deposition, landforms, surface runoff, and soil infiltration with radionuclide migration could be assessed using the Chernobyl site data. Lessons from analyses of these data could benefit waste disposal facilities or other decommissioning sites such as the Hanford site.

A simple detection method that holds promise for monitoring certain chemicals, particularly radionuclides, in the shallow subsurface was identified in the phytoremediation studies near Chernobyl. The phytoremediation studies demonstrated that chemicals (including radionuclides) are taken up by plant roots and concentrated in the plants stems and leaves. Really extensive and nonintrusive monitoring can be accomplished by sampling vegetation and analyzing for radionuclides and chemicals. Removal of radionuclides by harvesting grasses and other specially planted vegetation can enhance environmental restoration. Radionuclide movement through the unsaturated zone is complicated by heterogeneities and preferential flow processes such as fingering. An important consideration in understanding radionuclide migration and sorption is the amount of liquid flow that occurs in the fractures in rock and soil, as opposed to liquid embedded in the rock or soil matrix.

The discussion brought out the importance of conjunctive use of monitoring and characterization data with models to first identify and then improve the characterization needs at particular sites. This would lead to improved understanding, particularly in identifying and evaluating the possibility of ultimate concepts and modeling approaches (as well as a way to understand some of the uncertainties involved in making these long-term predictions). It is hoped that the conjunctive use of the data in the modeling studies will lead to improved models for making predictions, allowing us to investigate alternative options for future remediations. Understanding the uncertainties and possibilities for the future is really very important.

The cooperative work between American and Russian colleagues in joint projects has indicated that there is a wealth of well-collected data at Mayak, Tomsk, and perhaps Krasnoyarsk. These data provide a wealth of information for the testing and evaluation of models, and understanding concepts of migration in the subsurface. For example, Tomsk resembles a well-controlled experiment where data has been collected for about 50 years. Mayak, in some respects, is much the same, although probably a little more complicated. Experience at these sites indicates that understanding density effects is important, though many times we ignore the density effects when we look at plume migration. Some recent studies have shown that even slight variations in density cause quite a change in the migration of plumes.

Concerning monitoring wells, we could monitor the locations that might be in danger to the population. To locate the monitoring well, first try to understand the physics of what is happening in the contamination plume using models. It is good to design and construct monitoring wells based on modeling results because the monitoring well network would be based on the physics of the system and would be placed at critical locations. For example, at the Mayak site, permeability in the northern and southern side of Lake Karachai is smaller than the permeability to the east and west. Since Lake Karachai is on the topological high, we would expect the flow to go east and west. However, the flow of the contaminant plume is actually goes north-west and south-east. One explanation is that because the plume has a higher density, it goes to the bottom, and the bottom topography controls the flow direction. This is a very interesting and important lesson. We learned that we should not be looking just at the transmissivity field or the hydraulic gradients, but also the topography of the system's bottom to determine monitoring well locations. This kind of knowledge can be transferred to other types of high-density plumes such as Dense Non Aqueous Phase Liquid (DNAPL) plumes.

An alternative model of the Lake Karachai system is based on the bunching of the potential contours as one moves west. Consequently, some of the north-south movement may not be related to the bedrock topography; rather it could be related to anisotropy and the interpretation to the potential field. One reason for the anisotropy may be due to the interpretation of the potential field with high conductivity zones, particularly in the form of correlated faults. The detected presence of these correlated faults may not show up, especially when the general direction of the potential field is parallel to that direction. So there are a variety of alternative conceptual models that must be evaluated in the process of interpreting the flow field. Some of the emerging technology allows inverse modeling procedures to evaluate various conceptual models, as well as their uncertainty. Uncertainty can be used in an experimental design process to evaluate discriminatory kinds of monitoring or testing. This process can be carried out in the field to help us better understand the system.

One point about density-driven flow at a site such as Mayak, it could allow the creation of a new sink for contaminated solutions. A number of permeable fault zones exist in the basement rock of Mayak; the dense solution can sink into these fault zones, diffuse and become trapped in porous blocks of these fracture zones. It is a challenge to develop a problem-specific model because this problem cannot be solved by standard generally proposed simulators. To a certain extent, it is an important lesson that can help define directions for future research efforts.

To represent faults both as conductors of the fluids, and as ultimate permeable zones where these fluids may reside, we have to know much more about the fault zones. Some fault zones are permeable pathways while others are impermeable barriers. This has been borne out by mineral studies and by geothermal studies. Advancing technology must consider characterizing these pathways appropriately. Especially at Mayak with the presence of high-density fluid, it is very important to determine whether they are truly permeable pathways and could serve as residual zones for long-term sequestration of these fluids. As time passes, little by little the density-driven flow will decrease because of dilution and other processes to the point where the density-driven control will cease. Eventually, the bulk of contaminants would move with the major flow along the most permeable part of the aquifer which would dramatically change the overall pattern of the contaminant plume.

The chemical modeling studies by Dr. John A. Apps, Lawrence Berkeley National Laboratory and the Russian Academy of Science illustrate how truly important it is to understand the underlying chemical mechanisms that are taking place. Long-term predictions require a firm understanding of the evolution of both the flow and the chemistry. We have a tendency to look at how things are right now and plan monitoring and modeling activities based on how they are. We cannot emphasize too much that projecting on how things are going to be in the future is also very important. If the chemistry and chemical environment change in the future, as the more mobile material moves away, and the immobile part remains, then you have a different problem. If this occurs, there is a whole different regime for the material that has been left behind.

Another interesting aspect to the physics of system not generally considered is that the radioactive contaminant plume is heat producing. Because of this heat production, the system is subject to density changes. These temperature and density features produce new phenomena that need to be considered. Issues such as these and those previously outlined are interesting lessons learned from some of the Russian and Ukrainian case studies.

During the discussions, two participants presented short summaries of their specific research work. These are summarized below.

Dr. Philip E. Long, Pacific Northwest National Laboratory, presented a short summary of research on microbial aspects of contaminant transport. Long showed slides of transmission electron micrographs of *shewanella putrefaciens* bacteria (CN-32). The slides and their analyses illustrate that for redox-sensitive radionuclides such as technetium, interaction with microorganisms can be very important. These interactions could have a significant impact on possible natural attenuation and the effectiveness of certain remediation methods. Field work at Shiprock, New Mexico, on characterizing diverse microbial communities interacting with uranium plumes, demonstrated the role of microbes in reducing metals in radionuclides that are redox sensitive.

Dr. Marcel van der Perk, Utrecht University, the Netherlands, demonstrated how general environmental data and software for areas contaminated by the Chernobyl accident are disseminated as an operational geographical-information-system (GIS)-based Environmental Decision Support System (EDSS). This EDSS has been developed as part of the European Commission-financed RESTORE project ("Restoration of radioactively contaminated ecosystems") using the raster GIS package PCRaster. The RESTORE-EDSS comprises a GIS-embedded modeling tool to simulate the transfer of radionuclides in food chains based on the understanding of the nature of contamination, the geo-chemical, hydrological, and biological processes involved, and the different pathways for radiocesium. It can be used to estimate internal and external radiation exposures to humans.

The EDSS is applicable to a variety of ecosystems and accounts for spatial and temporal variation of the above-mentioned factors and human behavior. The overall aim of the EDSS is to identify vulnerable areas in terms of enhanced radionuclide transfer into food chains, and/or presence of 'critical population groups' that suffer enhanced internal and/or external exposure to radionuclides. Predictions made by the EDSS are based on maps of soil contamination, soil type, and land use; production and production rates; and consumption habits of the affected population. These spatial data have been made available for various areas in Ukraine, Belarus, and Russia at three different scale levels: entire contaminated area level (resolution 1 km x 1 km), district level (resolution 100 m x 100 m), and farm level (50 m x 50 m). Copies of the EDSS, including the spatial modeling software and data, can be requested directly from Marcel van der Perk.

CONCLUDING REMARKS

Near the end of the discussions, one participant asked the panel to comment on the research and challenges facing the hydrologic community in the next century. The responses, presented below, serve well to conclude this summary of the Round Table Discussion at the Fourth USA/CIS Joint Conference of Hydrologic Issues of the 21st Century.

The major challenge in the next hundred years is reflected by the news that the world's population has recently reached six billion people. How are we going to use our science of hydrology and hydrogeology to meet the needs of these people in a society that is becoming an urban society? Additionally, how can hydrologists affect or even overcome any negative impacts on water resources for the expanding population from future political and economic changes?

Taking into account the character of our problems at the Mayak and Chernobyl sites, and also in many places of the United States, it would be correct to say that much research is needed in the 21st century, and even in the forthcoming millennium, because the processes involved have very long time scales, perhaps hundreds of years. Technical meetings between the Commonwealth of Independent States (CIS) (formerly USSR) and the United States involving these general problems should take place more frequently to discuss these very dangerous problems. These meetings could also include our colleagues from other European countries, and be more practical. These meetings should be more focused on one or a few particular sites and specific objectives. Pushing ahead along these lines may well lead to greater successes.

What hydrology will be like in the 21st century is a very interesting question. We believe that hydrology should become a more comprehensive, more multi-faceted science involving not only purely hydrological or hydrogeological phenomena, but also many other processes that those phenomena generate. All the models that we are trying to develop often result from commendable effort, but the 21st century should see some concrete and down-to-earth solutions emanating from our modeling activities. And it is good for future conferences to bring together younger people who will go on to understand the processes we are studying better than we do.

It is obvious from these productive discussions that the more we can learn to work together on the problems that face us all over the world, the better off our entire society will be.

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